

Issues in Airborne Systems for Closely-Spaced Parallel Runway Operations

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ABSTRACT

Efforts to increase airport capacity include studies of aircraft systems that would enable simultaneous approaches to closely spaced parallel runways in Instrument Meteorological Conditions (IMC). The time-critical nature of a parallel approach results in key design issues for current and future collision avoidance systems. These issues are being studied in two ways. First, a part-task flight simulator study has examined the procedural and display issues inherent in such a time-critical task. Second, a prototype collision avoidance logic capable of generating this maneuver guidance has been designed using a recently developed methodology.

INTRODUCTION

To reduce flight delays and increase airport capacity, several methods of enabling closely spaced, independent parallel approaches in Instrument Meteorological Conditions (IMC) are being studied. Without specialized radar, current criteria allow independent parallel approaches to runways spaced 4300 feet or more apart; the use of new technologies to reduce this minimum separation would allow airports to effectively maintain their Visual Meteorological Conditions (VMC) capacity in IMC.

The task of ensuring adequate aircraft separation during parallel approach operations is very difficult. The aircraft are closer together than during any other airborne phase of flight, which severely limits the potential warning time should one aircraft blunder into the other's approach path. Studies have shown that, for runways at least 4300 feet apart, the controller using today's radar can ensure aircraft separation. [1] The Parallel Runway Monitor (PRM) system, which uses special radar with a high update rate, has been implemented at Raleigh-Durham and Memphis airports. Using special displays, Air

Traffic Controllers can determine if an aircraft will enter a 'No-Transgression Zone' (NTZ) between the two approach paths and can give each aircraft commands to steer away from a potential collision. Recent studies have concluded this system can be used to reduce runway separation to 3400 feet. [2,3]

Further reduction of the runway spacing using PRM has not been recommended. Not only are the required reaction times reduced, but aircraft, given the limits of their localizer tracking performance, may occasionally enter the NTZ while attempting to track the localizer, causing nuisance alerts and aborted approaches. [3]

Overview

This paper details two studies of airborne systems capable of ensuring adequate aircraft spacing during parallel approaches in IMC. First, a baseline flight simulator study examined the pilot responses to a potential collision, both with and without the aid of an alerting system. The current Traffic Alert and Collision Avoidance System (TCAS II) was used as the baseline alerting system. TCAS II was not designed for close parallel approaches, however, and would generate a high number of false alarms for runway separations less than 3000 feet [4]

The second study involved developing a prototype alerting logic specifically for parallel approach conditions. By taking into account the constrained aircraft trajectories during parallel approaches and by using cross-link of information between aircraft, the system can allow a further reduction of aircraft separation. Using a recently developed methodology, a probabilistic analysis of the system's performance has been made. [5] The performance of this system has been compared to both the performance of the pilots in the flight simulation study and the theoretical performance of the TCAS II system.

FLIGHT SIMULATOR STUDY

A preliminary simulator experiment had active airline pilots fly many parallel approaches on the MIT part-task Advanced Cockpit Simulator in order to study the pilot effectiveness in avoiding encroaching traffic, both with and without the aid of an alerting system. During each approach, traffic on a parallel approach (to runways separated by 4300 feet) would blunder towards the subject, and the subject's response was recorded to find the allowable maneuver strength and reaction time. The study also examined several cockpit traffic display enhancements, and the relative merits of flying the approach (before any avoidance maneuver) manually or on autopilot.

The MIT Advanced Cockpit Simulator provides pilots with the relevant controls and displays of a generic glass cockpit aircraft. A Silicon Graphics workstation provides the display of the glass cockpit screens and traffic displays; it also calculates the dynamics of the simulator, which has the performance of a Boeing 737. The pilot can use the Flight Management Computer, Mode Control Panel or sidestick to control the aircraft. An experimenter acts as co-pilot, setting gear, flap and autopilot settings as commanded by the subject.

A second Silicon Graphics workstation steered the 'intruder' aircraft on an approach parallel to the subject's, and then turned the intruder into the subject at a scripted point during the scenario. This Robust Situation Generation system made possible repeatable, scripted near-collisions while allowing flexibility for varied flight paths between pilots. [6]

The 18 subjects were qualified airline flight crew from two major airlines, with a mean of over 15,000 total flight hours. All but one were considered current on glass cockpit aircraft.

Each subject flew a total of 36 approaches. These approaches were flown in 12 blocks of three. Each of the 12 blocks were flown under a different condition, representing all the combinations of four different traffic displays and three different procedures. The test matrix was counter-balanced between pilots to reduce any learning effects.

The study tested four displays: a TCAS traffic display integrated with the Electronic Horizontal Situation Indicator (EHSI); enhancements to the current traffic display on the EHSI, including an indication of the localizer beams for both runways and a split screen; a

display of the parallel approach traffic on the pilot's Primary Flight Display (PFD); and a combination of the new displays on the PFD and EHSI.

Three procedures were studied: the subject monitors an autopilot approach, and then takes manual control to follow the alerts and avoidance maneuvers shown by a TCAS II - type system; the subject manually flies the approach, and follows the alerts and avoidance maneuvers shown by a TCAS II - type system; and the subject handflies the approach but is not shown any alerts or avoidance maneuvers.

Within each test block, each subject flew three approaches. Using Robust Situation Generation, these three approaches were scripted to each be one of three types. One represented an intruding aircraft that has overshoot its own localizer and is established on a collision course with the subject's aircraft. The next type represents an intruding aircraft that strays from its own approach course to a collision course. The final type represents an intruding aircraft that, while straying enough from its path to generate a TCAS Resolution Advisory (RA), is established on a trajectory that should cause it to pass at least 1000 feet away from the subject. Several different approaches were scripted for each type so that the subjects could not second guess when evasion maneuvers would be needed.

The primary goal is to ensure adequate separation between aircraft on parallel approaches. Therefore, the first measurement of interest is the resulting miss distance between aircraft. Overall, the intruder and subject aircraft came within 500 feet of each other 4% of the time, and within 1000 feet of each other 20% of the time. These percentages were found to be significantly lower when the approach was flown on autopilot and significantly higher when TCAS avoidance maneuvers were not displayed.

The characteristics of the avoidance maneuvers can be described as follows: the mean load factor of the pitch maneuver was .59 'G's and, when the subjects performed a turning avoidance maneuver, they used a mean bank angle of 19 degrees; given the part-task, fixed-based level of simulation, however, these values may not be exactly those which would be used in the real aircraft. The pilots' mean reaction time to a displayed alert was 3.0 seconds (discarding values beyond three standard deviations).

During 16% of the approaches the subjects performed an avoidance maneuver so early that a TCAS alert

was never given. These early go-arounds often occurred long before the intruder aircraft was straying from its proper approach path, and may indicate the pilots' concern over the unusual proximity of these aircraft. Significantly fewer early go-arounds were commanded during the approaches flown on autopilot.

With the presentation of a TCAS generated maneuver comes the assumption that the pilot will follow it, both by reacting within five seconds, and then by matching or exceeding the TCAS pitch command. However, examination of the trajectories after-the-fact has shown that the actual maneuvers flown by the pilots, when the TCAS maneuvers were shown, met the vertical maneuver commanded by the TCAS only 40% of the time.

No single causal factor of the low conformance rate can be isolated. Pilot reaction time alone does not show a strong effect. 66% of the pilots reacted within the five second allowance assumed by the TCAS system, and of these only 61% matched the displayed TCAS maneuver. Of the pilots who acted shortly before the alert or after the five second allowance (13% and 20% respectively), a significant number of pilots still matched what the TCAS guidance commanded (71% and 33% respectively).

Conformance to the (vertical) TCAS maneuver may be affected by the turning maneuvers that the pilots often performed at the same time. Overall, pilots did not turn in 32% of the approaches (ie. the maximum bank angle after the alert was less than five degrees); 34% of the time the pilots turned away from the intruder, 11% of the time pilots turned toward the intruder, and 23% of the time pilots turned one way and then another. Pilots who did not follow the TCAS maneuver turned away from the intruder significantly more often than pilots who followed the TCAS maneuver; this may suggest that the pilots, by executing a turn, felt a vertical maneuver was no longer required.

Pilots, given the enhanced traffic displays tested in this experiment, conformed significantly less often than when they were given the current TCAS II type traffic display. This may also suggest that pilots, given a more explicit traffic picture, may have felt a vertical maneuver was not longer required; this perception may have been erroneous, however, as more near-misses happened with these new displays.

Other possible factors for the low conformance rate have also been investigated. Examining the aircraft

trajectories for the approaches where the pilots were not shown any TCAS alerts or maneuver guidance, the pilots' reactions only satisfied what the TCAS would have commanded in 25% of the approaches, suggesting that the TCAS maneuver is not what the pilot would do instinctively. As well, the conformance rate varies widely between pilots, from a high of 68% to a low of 25%.

The mere presentation of the TCAS alerts caused a significant improvement in aircraft miss distance, whether or not the TCAS maneuvers were followed exactly by the pilots. As shown in Figure 1, more incidents were caused when the pilots were not shown alerts, regardless of whether their maneuver happened to match what TCAS would have commanded; when the pilots were shown alerts and an avoidance maneuver, far fewer incidents occurred. Significantly fewer incidents happened when the pilots, shown an avoidance maneuver, conformed to it.

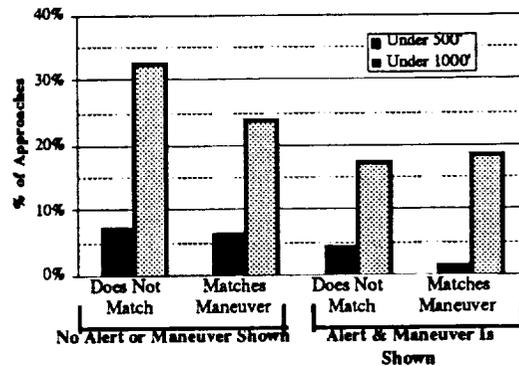


Figure 1. Frequency of Incidents With and Without Presentation of Alerts & Avoidance Maneuvers, and Pilot Conformance to Them

Pilot ratings during the debriefing showed an overwhelming preference for parallel approaches in IMC to be flown on autopilot; most pilots cited both decreased workload, which would allow them to monitor the parallel traffic better, and the reliability of the autopilot system.

Pilot rankings of the preferred role of the collision avoidance system showed a strong preference for a TCAS II - type alerting system, ie. one that provides avoidance maneuvers for the pilot to follow manually. A lack of any alerting system and a completely automatic avoidance system were ranked the lowest.

PROTOTYPE ALERTING LOGIC

A prototype alerting system logic was developed as the second study discussed in this paper. TCAS II uses the projected time to impact to determine whether an alert should be issued, and it has been successful in resolving several conflicts. However, when using TCAS for closely spaced parallel approaches, nuisance alarms can occur as the parallel traffic oscillates along its approach path. Furthermore, when parallel traffic does blunder, TCAS may not provide enough warning time to avoid an accident. It was felt that a specialized alerting system designed specifically for parallel approach could improve safety while producing fewer nuisance alerts than TCAS.

The prototype alerting system uses estimates of intruder position, heading, and bank angle to determine whether the intruder is in a position to potentially cause a collision. Differential Global Positioning System position accuracy is assumed, and heading and bank angle errors are assumed to be normally distributed with standard deviations of 2.5° and 5° respectively. Based on these errors, a probabilistic analysis of the parallel approach situation was performed to determine the probability of a collision. This approach was based on a previously-developed methodology to evaluate alerting system performance and to illustrate the tradeoffs between false alarms and accidents when alerting thresholds are designed. [5]

Given a particular intruder relative position, heading, bank angle, and velocity, the probability that a collision will occur was estimated using Monte Carlo simulations. These simulations assumed that the intruder aircraft flew a constant-rate turn and remained at the same altitude throughout the event.

To examine whether an alert based on a particular intruder state is appropriate, several potential future trajectories for the own aircraft were examined over a range of measured intruder positions, headings, bank angles, and velocities. Once an alert is issued the own aircraft performs an avoidance maneuver following a response delay. Several avoidance maneuvers were examined, including a $0.25g$ pitch up until a $2,000$ ft/min climb rate was achieved and a $10^\circ/\text{sec}$ rolling maneuver to a 30° bank angle, held until a 30° heading change away from the intruder was achieved. A combined climbing and turning maneuver was also examined. For comparison, the

miss distance achieved without an avoidance maneuver was also determined.

By examining the curves of collision probabilities for the two potential future trajectories of the own aircraft (non-maneuvering and maneuvering), it is possible to determine whether an alert is appropriate. For example, an alert should be issued when there is a high probability of a collision if the own aircraft does not maneuver. The probability of a collision, even when the own aircraft does maneuver, provides a measure of the timeliness of the alert: if this probability is also high, then the alert may be too late to prevent an accident.

Figure 2 shows a representative plot of two regions within which the probability of collision is greater than 0.001, both for a non-maneuvering and maneuvering own aircraft. The choice of probability levels of 0.001 is based on PRM safety levels.

In the situation shown in Figure 2, the own aircraft is shown at the origin. The intruder's measured heading is parallel to the own aircraft but the measured bank angle is 15° toward the own aircraft. If the intruder is located at position 1, then the probability of a collision, regardless of what the own aircraft does, is below 0.001 and an alert could be considered unnecessary. In effect, an aircraft at position 1 is unable to collide with the own aircraft without a great increase in speed. An intruder at position 2 is projected to collide with the own aircraft unless a climbing turn avoidance maneuver is performed, warranting an alert. An intruder at position 3 is projected to collide with the own aircraft if no avoidance maneuver is performed, but an alert could be delayed because time is yet available to collect information about the intruding aircraft's flight path.

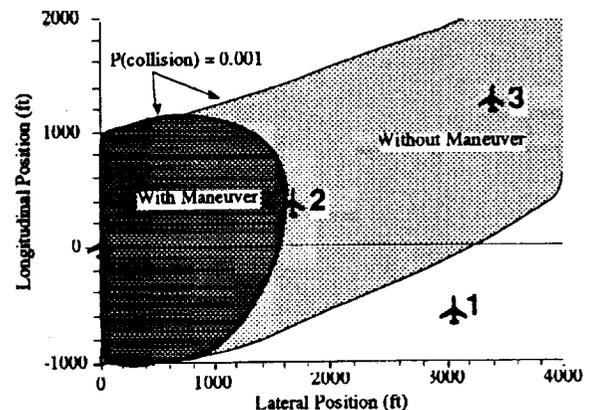


Figure 2.
Probability Contours and Alert Threshold

Thus, a prototype alerting threshold was constructed along the thick solid line in Figure 2. When the intruder crosses this threshold, the probability of a collision rises above 0.001 and an alert is issued. The own aircraft should then perform a climbing turn avoidance maneuver. A different threshold must be constructed for each combination of intruder heading and bank angle.

EVALUATION OF ALERTING METHODS

The prototype alerting method was compared to both the theoretical performance of TCAS II-type thresholds and to the achieved performance of pilots using the aircraft track data from the part-task simulation studies. When an alert was issued from the prototype system, the own aircraft was assumed to perform a climbing-turn maneuver following a 5 second delay. A TCAS-like system was also examined using slightly modified TCAS II alerting logic. When a TCAS alert was issued, the aircraft performed a vertical avoidance maneuver following a 5 second delay. Third, the achieved performance of pilots was also compared using the observed results from the study, for the cases where the pilots were and were not shown TCAS II-type maneuvers.

A collision was defined to occur if the distance between aircraft was below 500 ft at any time during the run. The behavior of the alerting system was classified into one of six categories, as summarized in Table 1.

Category	Correct Rejection	Correct Detection	False Alarm	Missed Detection	Insufficient or Late Alert	Induced Collision
Alert Issued?	No	Yes	Yes	No	Yes	Yes
Collision Without Maneuver	No	Yes	No	Yes	Yes	No
Collision With Maneuver	N/A	No	No	N/A	Yes	Yes

Table 1. Situation Outcome Categories

Category	Correct Rejection	Correct Detection	False Alarm	Missed Detection	Insufficient or Late Alert	Induced Collision
Pilot, Without TCAS II System	12%	3%	80%	1%	5%	4%
Pilot, With TCAS II System	8%	2%	86%	0%	2%	4%
Theoretical TCAS II Type System	13%	2%	79%	0%	4%	3%
Prototype Alerting System	54%	4%	39%	0%	2%	2%

Table 2. Comparison of Achieved and Theoretical Outcomes

Table 2 shows the following: the achieved performance by pilots during the flight simulation study, both when they were and were not shown alerts, and the theoretical performance of the exact TCAS II type system and of the prototype system.

The pilots' reactions were very conservative. The most false alarms were generated by the pilots when TCAS avoidance maneuvers were presented to them. However, without the presentation of TCAS avoidance maneuvers, some potential collisions were never spotted, resulting in collisions. In addition, the pilots' reactions, when required to avoid a collision, were usually strong enough to successfully evade the intruding aircraft; however, some pilot reactions caused an accident that otherwise would not have occurred.

The TCAS II-type maneuvers, flown automatically after a five second delay, were also very conservative, correctly detecting all possible intrusions but generating many false alarms. Like the pilots' maneuvers, the TCAS system caused some accidents; unlike the pilots' maneuvers, some TCAS maneuvers were of insufficient strength to successfully evade the intruder.

The prototype alerting system performed the best, with more correct detections and significantly fewer false alarms. However, the single type of avoidance maneuver flown after an alert was insufficient in some cases and caused collisions in others.

Further improvements to the prototype alerting system may help eliminate these remaining problems. This logic was designed assuming the intruder would perform a constant-rate turn at constant altitude and at constant airspeed. A significant portion of the Insufficient Alerts (64%) occurred in scenarios in which the intruder greatly increased airspeed during the interval between the alert and the closest point of approach. The development of alerting thresholds can easily be modified to accommodate such maneuvers resulting in system which can guarantee the same level of safety while minimizing false alarms.

Similarly, the alerting logic currently dismisses any information it receives about the intruder's climb rate. The logic senses a potentially dangerous situation and suggests a climbing turn avoidance maneuver, without regard to the climb rate of the intruder. A preliminary study of assigning avoidance maneuvers based on the intruder's climb rate has shown a significant decrease in the number of those false alarms which will cause accidents.

The False Alarm rate, while high, may also reflect that unusual proximity of the aircraft during close parallel approaches. An alert was termed a False Alarm if the own and intruding aircraft would have missed each other by more than 500 feet; this threshold may be less conservative than pilots are currently accustomed to. An investigation of the false alarm trajectories finds that the aircraft often would have missed by a distance less than 1000 feet, suggesting an alert was still valuable in these cases.

CONCLUSIONS

Both pilot comments and flight simulator results show the benefits of displaying to the pilot an avoidance maneuver for them to fly. Although the low conformance of pilots to their displayed TCAS maneuvers is surprising, it is difficult to determine whether it is good or bad. Numerical studies show that both the maneuvers flown by pilots and the maneuvers commanded exactly by the TCAS systems have their flaws. However, these results do show that pilot responses are variable and must be taken into account when designing a pilot-in-the-loop alerting system.

Numerical simulations provide several insights. The presence of an alerting system eliminates missed detections. Pilots and the TCAS II - type system are

conservative and generate many false alarms. The prototype system is successful in improving the correct detection rate while reducing the amount of false alarms.

Some improvements may be advisable for the prototype alerting system. Measurement of the intruder's relative velocity should be integrated into the design of the alerting thresholds. Also, further work should investigate updating the suggested avoidance maneuver based on real-time intruder state measurements.

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